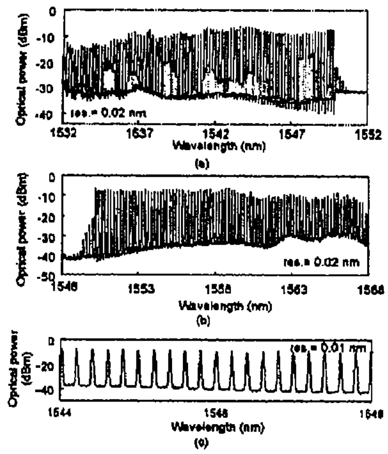

Fig. 4. Spectra in the loop without FBG-2

This indicates that a light with arbitrary wavelengths over a 30 nm (3.75 THz in frequency) range that exactly follow a frequency grid can be achieved with a variable FBG.

4. Conclusion

A novel configuration for a wavelength converter and a variable wavelength light source operating on strict frequency grid was proposed and demonstrated. The 375 GHz frequency shift as a wavelength converter and 3.7 THz-wide variable-wavelength light source are successfully demonstrated.

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FP6 **12:00 PM**

Integrated DQPSK Transmitter for Dispersion-Tolerant and Dispersion-Managed DWDM Transmission

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We demonstrate GaAs integration of an encoder for optical DQPSK transmission. Experiments demonstrate application to dispersion-tolerant 10 Gb/s transmission over an uncompensated fiber span up to 250 km, and high spectral efficiency 20 Gb/s transport.

1. Introduction

There is currently renewed interest in the development of differential phase-shift key (DPSK) for optical transmission, with increasing evidence that DPSK exhibits superior transmission performance compared to on-off-key (OOK) in DWDM transmission systems [1]. While binary DPSK has been recognized for many years, we have recently demonstrated quadrature signaling - DQPSK [2],[3] - where parallel bit streams are encoded to one of four possible phase states. Compared to conventional OOK, optical DQPSK offers improved tolerance to chromatic dispersion and polarization mode dispersion (PMD), together with increased spectral efficiency, while requiring the same OSNR for a given bit rate.

To enable wide application of optical DQPSK, integration of optical functionality is required to provide high performance, compact size and cost-effective manufacturing. Here we describe the realization of a high-functionality GaAs/AlGaAs single-chip DQPSK encoder, which we employ to demonstrate key features of optical DQPSK. We utilize the inherent advantages of DQPSK to address multiple applications: transmission of 10 Gb/s over 250km of SMF without dispersion compensation, and transmission of 20 Gb/s with high spectral efficiency.

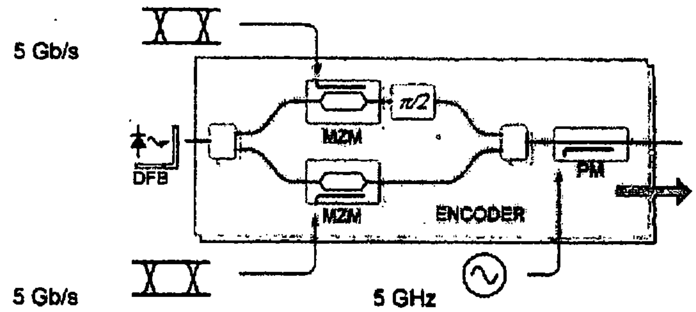


Figure 1: Schematic illustration of optical DQPSK encoder, showing configuration for 10Gb/s transmission.

2. Single-Chip GaAs/AlGaAs Optical DQPSK Encoder

As outlined in [2], an optical DQPSK link consists of digital precoder, electro-optic encoder, and an optical delay-and-add decoder used with balanced detection. Here we focus on the development of the encoder. While there are alternative encoder realizations which can provide mapping of electrical bits to optical phase states, our simulations suggest that best performance is achieved using Mach-Zehnder modulators (MZMs) arranged within a Mach-Zehnder super-structure, as shown in Fig. 1. Each of the MZMs is biased for minimum *dc* transmission and driven with a data signal with amplitude $2V_\pi$ at a bit rate $B/2$. An optical phase difference of $\pi/2$ is maintained between upper and lower branches, ensuring quadrature addition of the optical fields on recombination. A phase modulator (PM) is also shown in Fig. 1 after the recombiner, which can be driven with a sinusoidal clock signal to provide chirp on the DQPSK signal. As shown in the results below, additional chirp allows extended reach for uncompensated transmission.

For practical implementation, integration of these multiple functions is essential in order to reduce footprint, reduce assembly, and provide suitable stability. We have successfully integrated a DPQSK encoder like Fig. 1 onto a single chip using a GaAs/AlGaAs integration platform. This improves our previous design by incorporating the additional phase modulator, together with modifications which allow transmission experiments with long pattern lengths. The optical waveguides consist of ribs etched into the surface of a GaAs/AlGaAs slab-waveguide. Optical inputs to the twin, parallel MZMs are from a 1×2 splitter via compact S-bends. Similar S-bends furnished with phase-shift electrodes route the modulator outputs to the 2×2 optical combiner, a device that introduces a nominal $\pi/2$ phase difference between the two optical paths. Identical split and recombine elements are also used within each travelling-wave MZM. The MZMs use a microwave slow-wave technique to achieve the RF/optical velocity-match needed to achieve wide bandwidth with low drive voltage. The phase modulator at the output is a traveling wave structure similar to the Mach-Zehnder electrodes. A low-loss integrated two-photon absorption (TPA) monitor on the GaAs chip after the recombiner provides a photocurrent proportional to $\langle I(t)^2\rangle$, where $I(t)$ is the instantaneous output intensity. The TPA photocurrent, ~ 1μA, is equivalent to detection of the output signal with a fast photodiode followed by an RF diode detector. The RF power carried by the optical signal under DQPSK modulation is minimum at optimum bias, and provides a convenient error signal for closed loop control of the phase difference between upper and lower optical paths. The 52mm × 3.5mm GaAs/AlGaAs chip was co-packaged together with a DFB laser to provide a high-performance small-footprint module, shown in Fig. 2. Typical optical output power of 1 mW under DQPSK modulation was realized for several modules.

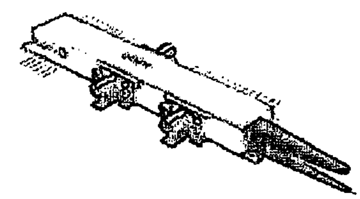


Figure 2: DQPSK transmitter module containing GaAs encoder together with DFB laser source.

3. Experimental Setup

Data from a pattern generator was used to provide inputs I_k and Q_k to the DQPSK encoder. Both data and complementary data outputs of the pattern generator were used, with a relative time delay of 2.2 ns to approximate uncorrelated data. For a net transmission rate of 10 (20) Gb/s, the pattern generator was clocked at 5 (10) GHz. The MZMs exhibited bandwidths ~ 15 GHz, with $V_\pi < 3.5$V. Standard 10 Gb/s drivers were used to amplify the signals to 7V peak-peak, corresponding to $2V_\pi$ for the MZMs. RF phase shifters were used to synchronize I_k and Q_k data terms. Each MZM was biased for minimum optical output in the absence of an RF signal.

A simplified decoder consisting of a single Mach-Zehnder interferometer (MZI) with balanced detection was used, and either output u_k or v_k could be measured by appropriate adjustment of the decoder phase. The MZI was a fiber interferometer with a commercial fibered receiver with 15 GHz bandwidth. For 10 (20) Gb/s operation, the nominal MZI delay was 200 (100) ps. For decoder stabilization, a control loop was implemented using a second pilot tone together with an RF diode detector after the balanced receiver. No precoder circuit was employed for measurement, and hence there was a deterministic mapping of data from input to output. To allow BER measurements, the error detector was programmed with the expected data sequence incorporating the DQPSK mapping. For transmission of real traffic, a precoding function is required as given in [2].

4. Dispersion-Tolerant Transmission

For ring architectures in metropolitan networks, dispersion-tolerant transmission is an attractive feature, since dispersion compensation adds considerable cost and complexity. DQPSK provides inherent dispersion tolerance since data is transmitted at a symbol rate half that of the channel bit rate. For transmission at 10 Gb/s over standard

singlemode fiber with dispersion ~ 17 ps/nm.km, DQPSK can provide reach up to 150 km, providing significant improvement over conventional on-off-key. Further improvement is realized, however, by additional chirp generated by a phase modulator at the encoder output. With a small sinusoidal modulation of ~ 0.2 rad amplitude, correctly phased with the data, substantially greater reach can be achieved. Whereas this synchronous phase modulation can improve dispersion tolerance, even small values of chirp within the individual MZMs of the encoder are detrimental to transmission.

Transmission was performed over SMF28 fiber with dispersion 15.8 ps/nm.km at 1535 nm. Measurements were performed for 10 Gb/s transmission using 2^{21}-length modified PRBS patterns. Excellent back-to-back sensitivity of DQPSK was achieved, demonstrating the high waveform quality achieved from the transmitter. By driving the phase modulator at the clock frequency and optimizing amplitude and relative phase, low dispersion penalty was recorded for spans up to 250 km, as shown in the results in Fig. 3a and 3b.

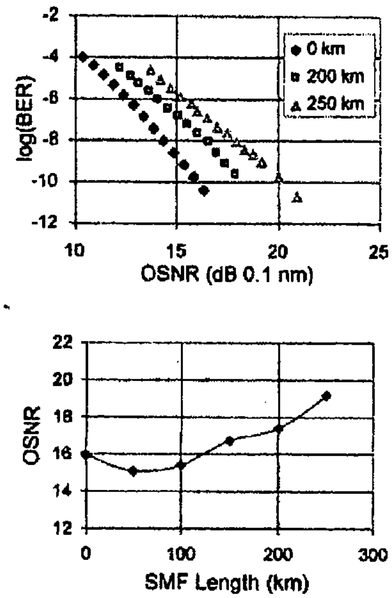


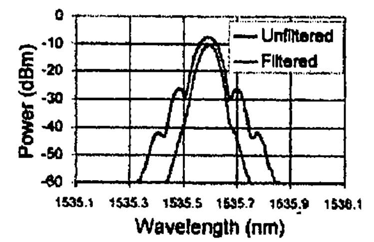
Figure 3: (a) measured BER as a function of OSNR; (b) required OSNR to achieve a BER of 10^{-9}.

Dispersion-Managed Transmission

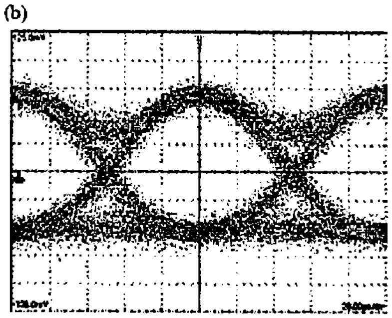
To make most efficient use of fiber infrastructure for long-haul transmission, it is desirable to maximize the spectral efficiency of optical transport. For point-to-point systems where dispersion management is employed, 20 Gb/s DQPSK offers an attractive option. At this data rate, DQPSK effectively provides parallel transmission of two OC-192 data streams on a single optical channel, providing increased capacity while maintaining a standard interface. Since transmitting 2 bits per symbol inherently halves the optical spectral width compared to binary signalling, DQPSK offers increased channel packing, potentially allowing 20 Gb/s transmission with 25 GHz channel spacing without the need for polarization interleaving/multiplexing to reduce cross-channel interaction.

To illustrate the potential spectral efficiency of DQPSK, we have demonstrated tolerance to tight optical filtering, which is a requisite for close channel spacing. A 20 Gb/s DQPSK signal was generated with the same encoder setup as above, but with the pattern generator clocked at 10 GHz. Here additional phase modulation was not applied. For decoding, an optical add-and-delay filter with 100ps delay was employed. To perform optical filtering, a 50 GHz de-interleaver operating in loop-back was used together with an optical circulator, providing an optical filter with FWHM 11 GHz. The 20 Gb/s DQPSK optical spectrum before and after optical filtering is shown in Fig. 4(a). The spectral width after filtering was 6.9 GHz, measured with 2 GHz resolution bandwidth. The narrow width of the DQPSK spectrum provides excellent tolerance to optical filtering, as demonstrated by the eye diagrams at the receiver shown in Fig 4(b) and Fig 4(c). Required OSNR to achieve a BER of 10^{-9} before and after filtering was measured to be 19.3 dB and 21.6 dB respectively. We expect that optimization of the optical filter will allow DWDM transmission with a spectral efficiency of 0.8 b/s/Hz.

(a)



(b)



(c)

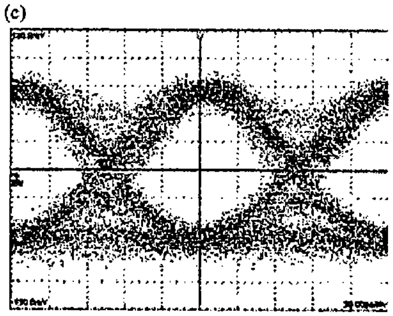


Figure 4: (a) Measured 20 Gb/s DQPSK optical spectrum; (b) 20 Gb/s received eye without optical filtering; (c) 20 Gb/s received eye after optical filter with 11 GHz FWHM.

5. Summary

A multi-function single-chip DQPSK encoder fabricated in GaAs/AlGaAs has been co-packaged together with a DFB laser to realize an integrated DWDM DQPSK transmitter module. Experiments using the module have demonstrated key advantages of DQPSK for dispersion-tolerant and dispersion-managed operation. Transmission of 10 Gb/s over 250 km of uncompensated fiber has been demonstrated. For 20 Gb/s operation, optical filtering with 11 GHz FWHM has shown low power penalty, illustrating the potential for high spectral efficiency in long-haul DWDM systems.

6. References

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FP7 **12:15 PM**

Suppression of Optical Harmonics in Wavelength Conversion Using Optical Single-Sideband Modulator

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For wavelength conversion using an optical SSB modulator, we proposed a novel technique for suppression of undesired harmonics, which gives the conventional theoretical limit of SNR, by feeding the fundamental and 3rd order harmonic rf-signals.

1. Introduction

In wavelength-domain-multiplexing (WDM) optical networks, wavelength conversion is a key technology for cross-connection at switching nodes [1]. Nonlinear effect between lightwaves whose wavelength are different, such as four-wave-mixing in optical fibers, cross phase modulation in semiconductor optical amplifier, and so on, are often used to obtain wavelength conversion, by which bit-stream data on a WDM channel can be copied to the other channel [2]. Pumping light sources are used in these techniques, so that the switching time from one WDM channel to the other channel is dominated by that of the pumping light source. The wavelength can be tuned by changing temperature or current density in the light source. But, it is difficult to change the wavelength in a few nano second without losing stability of the source. Recently, we reported wavelength conversion by using an optical single-sideband (SSB) modulator consisting of four optical phase modulators [3-6]. The wavelength of the output lightwave depends on rf-signal frequency and dc-bias voltage fed to the modulator, which can be electronically controlled. We demonstrated high-speed wavelength switching using an SSB modulator and a fiber Bragg grating [7]. By sweeping the rf-signal frequency, we get a photonic sweeper whose output wavelength can be swept agilely. This is useful for precise measurement of optical components for WDM systems. However, the output lightwave contains undesired components due to imperfection of the modulator and the electric signal feeding circuits, which decreases signal-to-noise-ratio (SNR) of the output. In addition, optical harmonic generation in phase modulations also causes a drop of the SNR. The effect due to the imperfection can be reduced by improvement of the modulator and circuits. On the other hand, the optical harmonic generation gives the theoretical limit of the SNR in the wavelength conversion using an SSB modulator as reported in previous works [3,4]. In this paper, in order to increase the SNR larger than the conventional theoretical limit, we propose a novel technique to reduce the optical harmonic generation by feeding two rf-signals whose frequencies are fm (fundamental) and 3fm (3rd order).

2. Principle of operation

Fig.2 Principle of operation

The SSB modulator consists of parallel four optical phase modulators as shown in Fig.1. The phases of electric field induced on the phase modulators are 0, 90, 180 and 270 degrees. The SSB modulator has a pair of Mach-Zehnder structures, so that we can apply rf-signals of 0, 90, 180 and 270 degrees by feeding a pair of rf-signals with 90 degrees phase difference at two rf-ports (RF A/ RF B) [6]. The rf-signals can be obtained by using rf 90 degrees hybrid coupler. The optical phase differences are also 90 degrees. Amplitudes of electric fields and lightwaves should be balanced. When the intensity of the electric field is so small that we can neglect high-order harmonic generation at the optical phase modulation, the output optical spectrum consists of only one component